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# MODELLING TIRE-SOIL INTERACTION WITH THE FEM APPLICATION

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**Summary.** This article presents the application of CAD systems with the use of the finite element method (FEM) in calculations of particular parameters of the tire-soil interaction. Moreover, a distribution model of surface pressures is presented as well as calculations of stresses in the soil with the FEM application. The obtained theoretical findings resulted in a comparative analysis of the value of designated stresses with those obtained through empirical studies, carried out both in a laboratory (soil channel) and also in field conditions, conducted in the Federal Agricultural Research Center - Braunschweig (Germany).

**Key words:** tire-soil interaction, computer-assisted design, finite elements method, stresses in soil.

## INTRODUCTION

The interaction of the drive unit with the ground is very significant not only for agrotechnological reasons, but also due to traction. Consequently, it is necessary for the drive mechanisms of machines and equipment moving on deformable ground to exert the least possible unitary pressure, and simultaneously to obtain maximum traction power in given conditions, such as pull force ($P_u$), or drive force ($P_j$). Unitary pressures occurring on the tire contact surface with the ground are directly connected with the phenomenon of their diffusion into the area on which the drive unit moves, both lengthwise and crosswise in relation to the movement direction. The range of their diffusion is a separate issue.

This study aims at applying modern methods of analysis with the application of CAD systems and FEM. This is of great importance due to economic reasons since field and laboratory research studies require incurring substantial financial costs, in view of high prices of measuring appliances and the necessity of holding a properly prepared terrain.

The influence of farming vehicles and machinery on the soil environment, through drive units, results in both the intended and side effects. The negative influence of drive units on the natural soil environment while performing activities connected with cultivating soil belong to the latter category. From this point of view, it is possible to distinguish between quantitative and qualitative deformations.

In the modern farming technology there is a tendency to increase powers of traction drive mechanisms of tractors and self-propelled farming machinery parallel to reducing the degree of soil packing (qualitative deformation). The increase in the pressure exerted on soil results in the increase in the drive force value, which directly affects the towing power value. This has caused the necessity of determining dependences describing the impact of drive mechanisms on soil. In the subject-related literature there exist numerous theoretical works and results of laboratory research concerning the issue described here.

In recent times, owing to a dynamic development of computer systems, it has been possible to apply modern numerical computer technology in order to analyze the tire-soil interaction. One of the methods applied to calculate particular parameters of the interaction between the drive mechanisms and soil is FEM (Finite Element Methods).

In this article the results of research study with the use of CAD systems have been presented, particularly the finite element method (FEM), in calculations of particular parameters of the tire-soil interaction. It was vital to verify available tools for solid modeling and FEM calculations from the perspective of their usefulness for calculating pressures in soil under particular tires while driving a farming machine.

## SOLID MODELS OF DRIVE TIRES

This work presents the scope of works related to the FEM application in analyzing the propagation of stresses in the soil medium following the influence of a particular tire used for self-propelled farming machinery. Solid models of drive tires were made, including all the basic elements constituting their structure. One of the research stages was the elaboration of the model of tire-ground (soil) interaction taking into consideration the system's dynamics. Modeling the ground consisted in performing computer simulations of the tire imprint as well as in determining geometrical features of the shape left during the drive.

Then the distribution model of surface stresses was prepared, as well as calculations of stresses in the soil, with the application of the finite element method. The analysis of the obtained results in the form of chart of stresses was conducted in particular cross sections of the tire-soil geometrical model.

The theoretical findings obtained resulted in a comparative analysis of the value of designated stresses with those obtained through empirical studies, carried out both in a laboratory (soil channel) and also in field conditions, conducted in the Federal Agricultural Research Center - Braunschweig.

The tire model was made in the CAD Inventor system. Subsequent operations, such as sketching, simple and complex stretching, dragging, rounding etc. resulted in a solid which was a virtual model of the tire under examination. As the pattern for building the model, the following tire was used: Stomil 14.9-28/8PR.

## THE TIRE-SOIL INTERACTION MODEL, INCLUDING THE SYSTEM DYNAMICS

The 3D tire model made in the Inventor system was used for shaping the imprint in the ground. The tire imprint was divided into a set of elementary surfaces to which forces were applied, normal and tangent components. The diagram below (Fig. 1) shows forces affecting the wheel and their distribution on the elementary surface of the imprint.

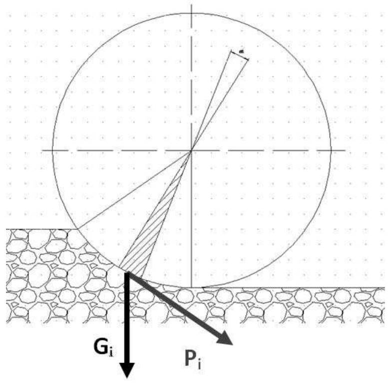


Fig. 1. Diagram of distribution of forces on a particular element of the imprint

Elementary components $P_i$ as well as $G_i$ were calculated according to the following dependences:

$$G_i = \frac{G}{n},$$

$$P_i = \frac{M}{nR},$$

$$P_i = \sqrt{P_{ix}^2 + P_{iy}^2},$$

$$P_{ix} = P_i \cos(i\alpha_i),$$

$$P_{iy} = P_i \sin(i\alpha_i),$$

where:
G – wheel load force,
M – moment of force imposed on the wheel,
R – tire rolling radius,
$P_i$ – elementary force tangent to a sector of the tire contact surface with the soil occurring as a result of the moment (M) interaction,
$P_{ix}$, $P_{iy}$ – components of force ($P_i$),
$\alpha_i$ – elementary angle of wrap,
n – number of elementary surfaces,
i – number of an elementary surface.

Figure 2 shows a fragment of the modeled imprint, formed through the tire impact on soil, which was divided into elementary surfaces. To each of these surfaces a tangent force $P_i$ was applied, which was described by the dependence. Force (G) was distributed evenly on particular elementary surfaces of the imprint.

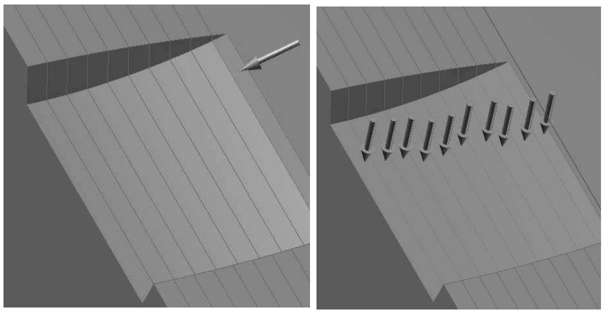

Fig. 2. Model of applying normal and tangent forces to a particular tire imprint sector

On establishing peripheral conditions, the ANSYS module of the Inventor system was used in order to determine pressures in the soil. Calculations were carried out for particular values of force (G) and moment (M).

## PERFORMING CALCULATIONS OF STRESSES AND THEIR ANALYSIS WITH THE APPLICATION OF THE FINITE ELEMENT METHOD

The first case to be analyzed in the ANSYS system was the model of loading the wheel with force (G)=7kN as well as moment (M)=0 Nm, i.e. the static load test. Then, analogous calculations as in the previous case were conducted, with the difference that the moment of force (M=5000 Nm) of the tire impact on soil was taken into account. The results of the conducted calculations, as well as the trend lines determined as exponential functions (Fig. 3) show that the increase in the moment of force affecting the imprint surface causes the reduction in the value of stresses on comparable depths of the ground.

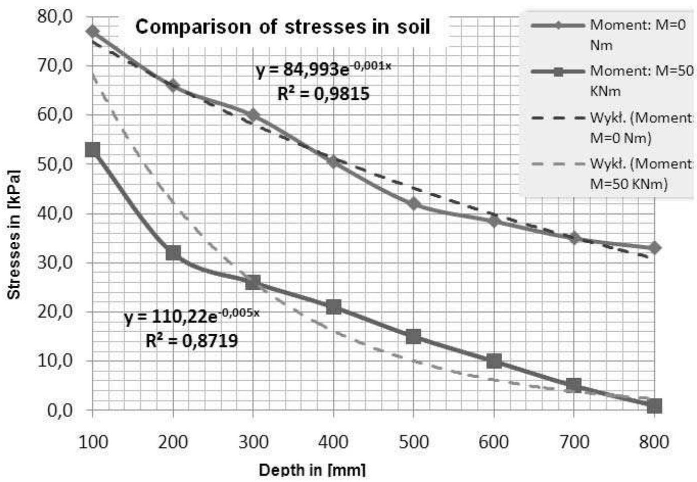


Fig. 3. Comparison of stresses in soil for the moments of 0 and 5 kNm at force G=7 kN

Then, a series of research studies were carried out for load cases analogous to the example above, with the difference that force (G) equaled 10 kN (Fig. 4).

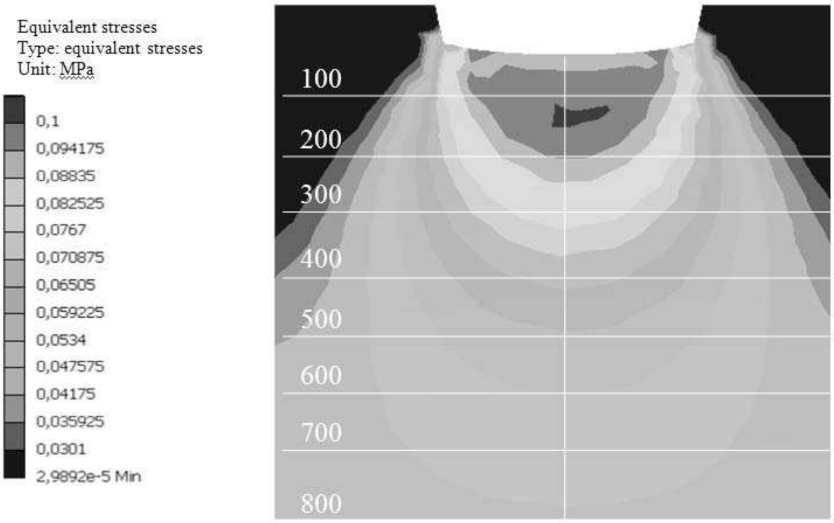


Fig. 4. Distribution of stresses in soil (M=0 Nm, G=10kN, levels in mm)

The analysis of results for the cases when (M=0 Nm, G=10kN) as well as when (M=5000Nm, G=10kN) demonstrates that also in such cases applying the moment of force results in the decrease in stresses. The difference in the value of stresses on particular ground depths approximately indicates a steady tendency, which can also be determined when observing the course of trend lines (Table 1, Fig. 5).

Table 1. Comparison of obtained results

| **Depth [mm]** | **100** | **200** | **300** | **400** | **500** | **600** | **700** | **800** |
|---|---|---|---|---|---|---|---|---|
| **M=0Nm, G=7kN** | 77.0 | 66.0 | 60.0 | 50.5 | 42.0 | 38.5 | 35.0 | 33.0 |
| **M=50*$10^2$Nm, G=7kN** | 53.0 | 32.0 | 26.0 | 21.0 | 15.0 | 10.0 | 5.0 | 1.0 |
| **M=0Nm, G=10kN** | 98.0 | 94.0 | 73.0 | 63.0 | 59.0 | 55.0 | 47.0 | 41.0 |
| **M=50*$10^2$Nm, G=10kN** | 76.0 | 56.0 | 48.0 | 41.0 | 28.0 | 21.0 | 15.0 | 7.0 |

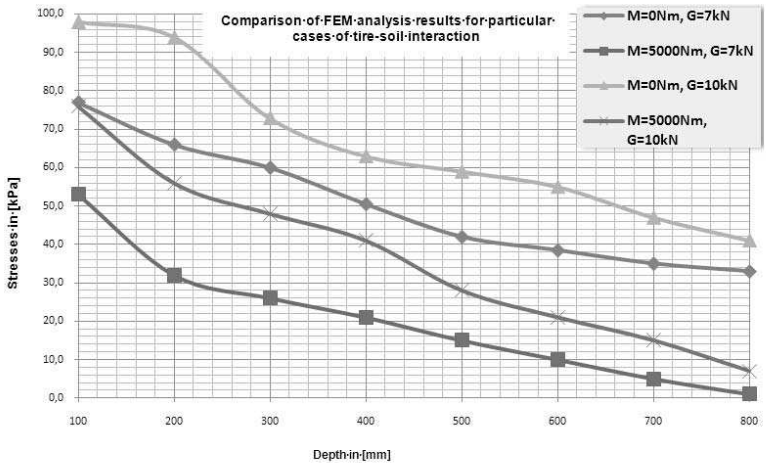


Fig. 5. Comparison of FEM analysis results for examined cases of tire-soil interaction

## VERIFICATION OF CALCULATION METHODS PROPOSED THROUGH COMPARISON WITH RESULTS OBTAINED IN FIELD TESTS

The results obtained with the FEM application were compared with laboratory results carried out for the Stomil 14.9-28/8PR tire, which was modeled for the purposes of the simulation conducted with the use of the ANSYS system. The results obtained in laboratory and field tests were used for the comparative analysis.

Fig. 6. Measuring instruments in the Federal Agricultural Research Center (FAL) in Braunschweig

Source: Jakliński L.: Mechanika układu pojazd-teren w teorii i badaniach (Mechanics of vehicle-terrain systems in theory and tests) Wybrane zagadnienia (Selected issues), OWPW 2006

Laboratory and field studies were conducted in the Federal Agricultural Research Center (FAL) in Braunschweig. The sand-clay ground measuring 100m x 40m was examined. Four hydraulic pressure sensors were used for measuring pressures, buried in the soil with their measuring heads situated exactly in the center of the wheel track.

The pressures measurement results compared to the values calculated in the FEM system were presented in Table 2. The distribution of pressure values in the plane parallel to the wheel track axis at three measurement depths was presented for G=7 kN and G=10kN, at M=50Nm.

Table 2. Comparison of results obtained in laboratory tests and FEM calculations (values of stresses in [kPa])

| **Depth [mm]** | **G=7kN** | | | **G=10kN** | | |
|---|---|---|---|---|---|---|
| | **$P_{FEM}$** | **$P_{meas}$** | **Difference [%]** | **$P_{FEM}$** | **$P_{meas}$** | **Difference [%]** |
| **100** | 77.0 | 85.6 | 10% | 98.0 | 108.2 | 9% |
| **200** | 66.0 | 59.4 | 11% | 94.0 | 88.1 | 7% |
| **300** | 60.0 | 44.0 | 36% | 73.0 | 61.4 | 19% |

Measurement results and those calculated with the FEM indicate significant similarity (approx. 9% error difference) for smaller ground depths. At greater depths the differences between measurements and calculations exceed even 20%, which can result from several factors:

- the geometrical model of the tire and its imprint in the ground was of insufficient accuracy,
- using approximate material properties for the ground model,
- approximate model of peripheral conditions used in FEM,
- insufficient density of the FEM grid of the calculation model (increased speed of calculations).

In order to improve the accuracy of calculations, the geometrical models of the ground and of the tire interacting with it should be better prepared in further research studies; the accuracy of the FEM model should be improved; the physical data characterizing the ground should completely correspond to the actual properties of the soil examined in laboratory conditions.

## CONCLUSIONS

The results of the obtained calculations have been presented in the form of color maps, tabular comparisons and diagrams. The analysis of theoretical calculations showed a similarity of the calculated values of stresses obtained through empirical studies, carried out both in a laboratory (soil channel) and also in the field conditions, conducted in the Federal Agricultural Research Center - Braunschweig.

The application of CAD systems as well as digital simulation methods and FEM calculations in the issues under discussion gives measurable advantages, among others the ones as follow:

- a significant reduction in time needed for research and independence of the research process from weather and climatic conditions,
- relieving the research team of routine and uncreative activities - time-consuming preparation of research stands, and laborious analyses of results,
- facilitating the performance of comparative analyses of tires under examination, as well as types of ground,

- conducting reliable research studies with the application of computer systems at the stage of the tire design and drive unit, without the necessity to carry out costly and time-consuming laboratory research.

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## MODELOWANIE ODDZIAŁYWANIA OPONY NA GLEBĘ Z ZASTOSOWANIEM METODY ELEMENTÓW SKOŃCZONYCH (MES)

**Streszczenie.** W opracowaniu przedstawiono zastosowanie systemów CAD z wykorzystaniem metody elementów skończonych (MES), w obliczeniach wybranych parametrów współpracy opony z glebą. Ponadto wykonano model rozkładu nacisków powierzchniowych oraz obliczenia naprężeń powstałych w glebie z zastosowaniem MES. W następstwie uzyskanych wyników obliczeń teoretycznych została przeprowadzona analiza porównawcza wartości wyznaczonych nacisków z uzyskanymi wynikami w trakcie badań laboratoryjnych (kanał glebowy) jak i w warunkach polowych, przeprowadzonych w Federal Reserch Centre – Braunschweig (Niemcy).

**Słowa kluczowe:** oddziaływanie opony na glebę, komputerowo wspomagane projektowanie, metoda elementów skończonych, propagacja naprężeń w glebie.